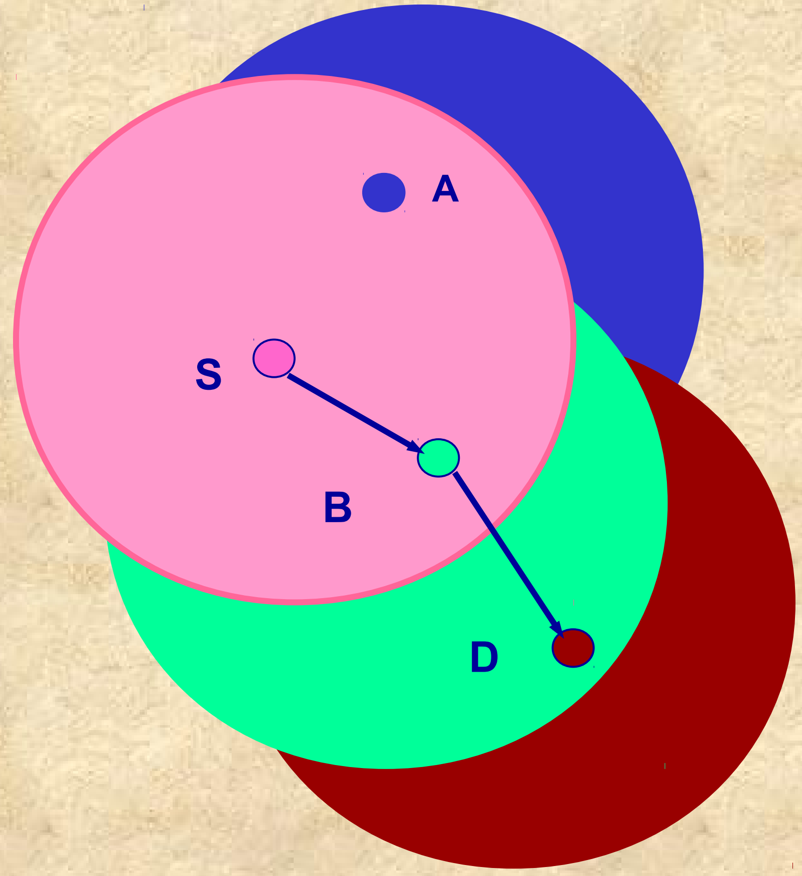
Chapter 2 Routing in Ad hoc Networks

Table of Contents

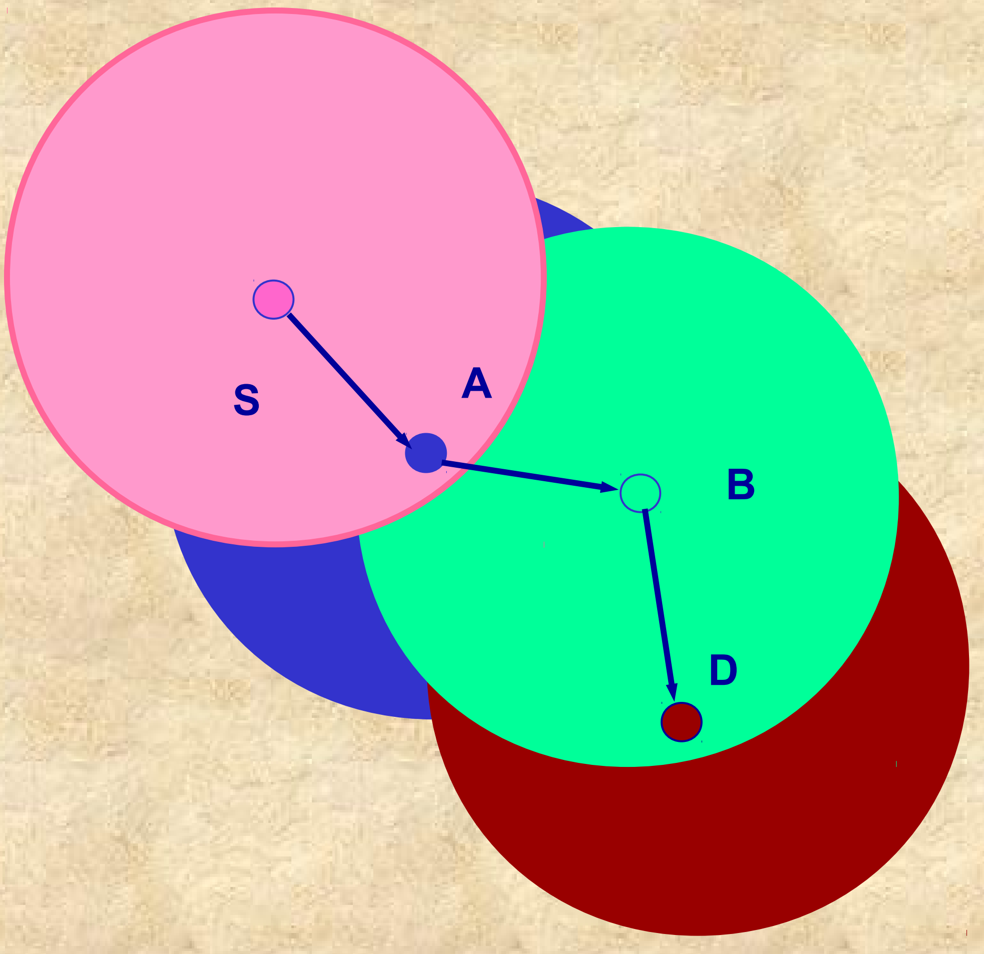
- Introduction
- Topology-Based versus Position-Based Approaches
- Topology-Based Routing Protocols
  - Reactive Routing Approach
  - Hybrid Routing Approach
  - Comparison
- Position-Based Routing
  - Principles and Issues
  - Location Services
  - Forwarding Strategies
  - Comparisons
- Other Routing Protocols
  - Signal Stability Routing
  - Power Aware Routing
  - Associativity-Based Routing
  - QoS Routing
- Conclusion and Future Directions

Illustration of Multi-hop MANET

Each color represents range of transmission of a device



MH S uses B to communicate with MH D



Due to movement of MHs, S now uses A and B to reach D

Routing Protocols

Topology-Based

- Depends on the information about existing links

- Position-Based Approaches
- Proactive (or table-driven)
  - Traditional distributed shortest-path protocols
  - Maintain routes between every host pair at all times
  - Based on periodic updates; High routing overhead
  - Example: DSDV (destination sequenced distance vector)

- Reactive (On-Demand) protocols
  - Determine route if and when needed
  - Source initiates route discovery
  - Example: DSR (dynamic source routing)

- Hybrid protocols
  - Adaptive: Combination of proactive and reactive
  - Example: ZRP (zone routing protocol)

Routing Approaches

Topology-Based

Depends on the information about existing links to forward packets

- Position-Based Approaches *Sender uses location service to determine the position of Destination node*
  - *[Physical location of each or some nodes determine their own position through GPS or some other positioning technique]*

Topology-Based

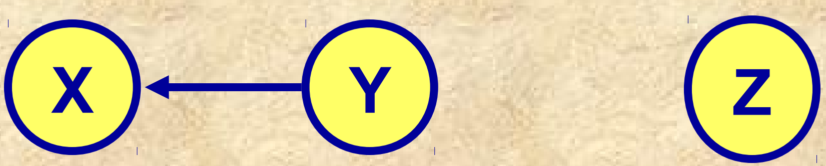
- Proactive (or table-driven)
  - Node experiences minimal delay whenever a route is needed
  - May not always be appropriate for high mobility
  - Distance-vector or link-state routing
- Reactive (or on-demand)
  - Consume much less bandwidth
  - Delay in determining a route can be substantially large
- Hybrid protocols
  - MHs determine their own position through GPS
  - Position-based routing algorithms overcome some of the limitations

Proactive Routing Approaches

- **Destination-Sequenced Distance-Vector (DSDV) Protocol**
  - **A proactive hop-by-hop distance vector routing protocol**
  - **Requires each MH to broadcast routing updates periodically**
  - **Every MH maintains a routing table for all possible destinations and the number of hops to each destination**
  - **Sequence numbers enable the MHs to distinguish stale routes from new ones**
  - **To alleviate large network update traffic, two possible types of packets: full dumps or small increment packets**
  - **The route labeled with the most recent sequence number is always used**
  - **In the event that two updates have the same sequence number, the route with the smaller metric is used in order to optimize (shorten) the path**

Destination-Sequenced Distance-Vector (DSDV)

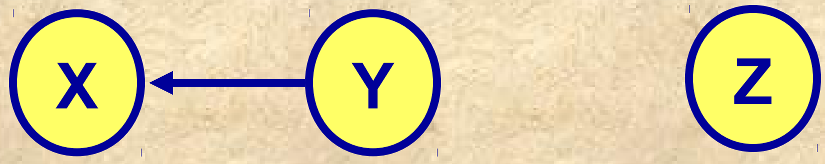
Assume that MH X receives routing information from Y about a route to MH Z



Let S(X) and S(Y) denote the destination sequence number for MH Z as stored at MH X, and as sent by MH Y with its routing table to node X, respectively

Destination-Sequenced Distance-Vector (DSDV)

MH X takes the following steps:



- **If S(Y) > S(X), then X ignores the routing information received from Y**
- **If S(Y) = S(X), and cost of going through Y is smaller than the route known to X, then X sets Y as the next hop to Z**
- **If S(Y) < S(X), then X sets Y as the next hop to Z, and S(X) is updated to equal S(Y)**

Proactive Routing Approaches

- The Wireless Routing Protocol
  - A table-driven protocol with the goal of maintaining routing information among all MHs
  - Each MH maintains four tables: Distance, Routing, Link-cost, and the Message Retransmission List (MRL) tables
  - Each entry in MRL contains the sequence number of the update message
  - MHs keep each other informed of all link changes through the use of update messages
  - MHs learn about their neighbors from acknowledgments and other messages
  - If a MH does not send any message for a specified time period, it must send a hello message to ensure connectivity

Proactive Routing Approaches

- ***Topology Broadcast based on Reverse Path Forwarding Protocol***
  - **Considers broadcasting topology information (including link costs and up/down status) to all MHs**
  - **Each link-state update is sent on every link of the network though flooding**
  - **Communication cost of broadcasting topology can be reduced if updates are sent along spanning trees**
  - **Messages are broadcast in the reverse direction along the directed spanning tree formed by the shortest paths from all nodes to source**
  - **Messages generated by a given source are broadcast in the reverse direction along the directed spanning tree formed by the shortest paths from all MHs (nodes) to the source**

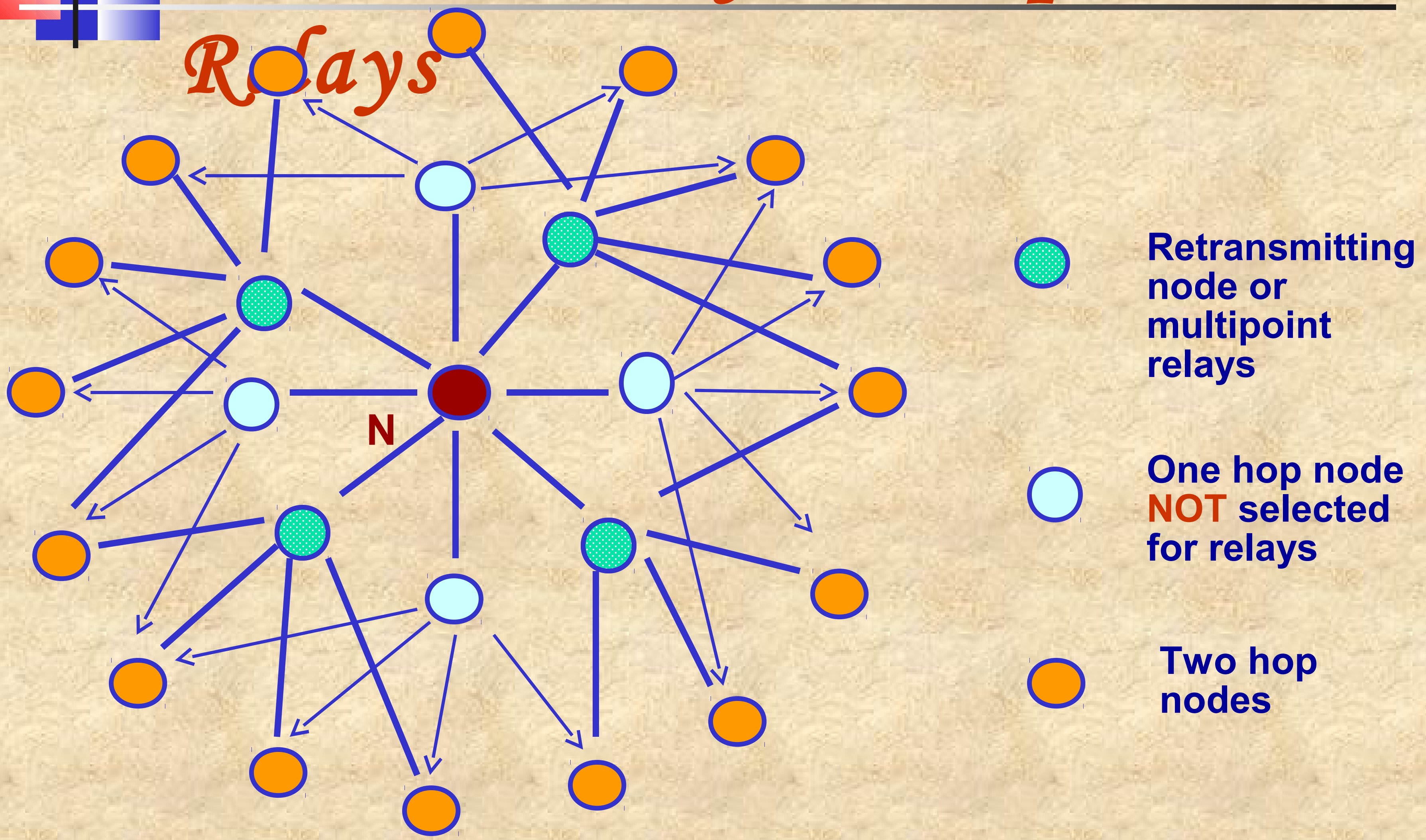
Proactive Routing Approaches

- *The Optimized Link State Routing Protocol*
  - Based on the link state algorithm
  - All links with neighboring MHs are declared and are flooded in the entire network
  - Minimizes flooding of this control traffic by using only the selected MHs, called multipoint relays
  - Only normal periodic control messages sent
  - Beneficial for the traffic patterns with a large subset of MHs are communicating with each other
  - Good for large and dense networks
  - An in-order delivery of its messages is not needed as each control message contains a sequence number

Proactive Routing Approaches

- *Multipoint Relays*
  - Minimize the flooding of broadcast packets in the network by reducing duplicate retransmissions in the same region
  - Each MH selects a set of neighboring MHs, to retransmit its packets and is called the multipoint relays (MPRs)
  - This set can change over time and is indicated by the selector nodes in their hello messages
  - Each node selects MPR among its one hop bi-directional link neighbors to all other nodes that are two hops away

Illustration of Multipoint Relays



Dynamic Source Routing

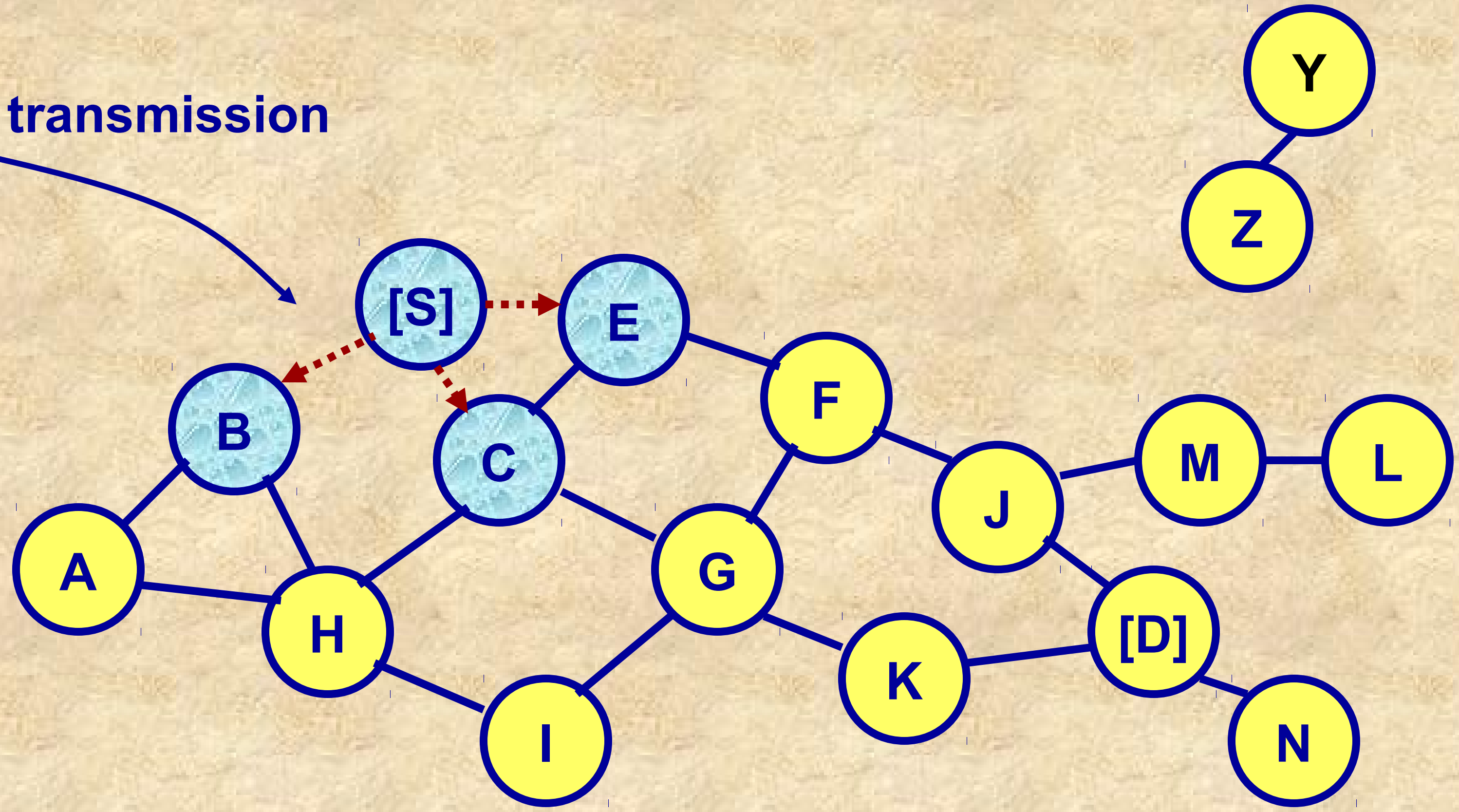
- **When MH S wants to send a packet to MH D, but does not know a route to D, MH S initiates a route discovery**

- **Source node S floods Route Request (RREQ)**

- **Each MH *appends own identifier* when forwarding RREQ**

Route Discovery in DSR

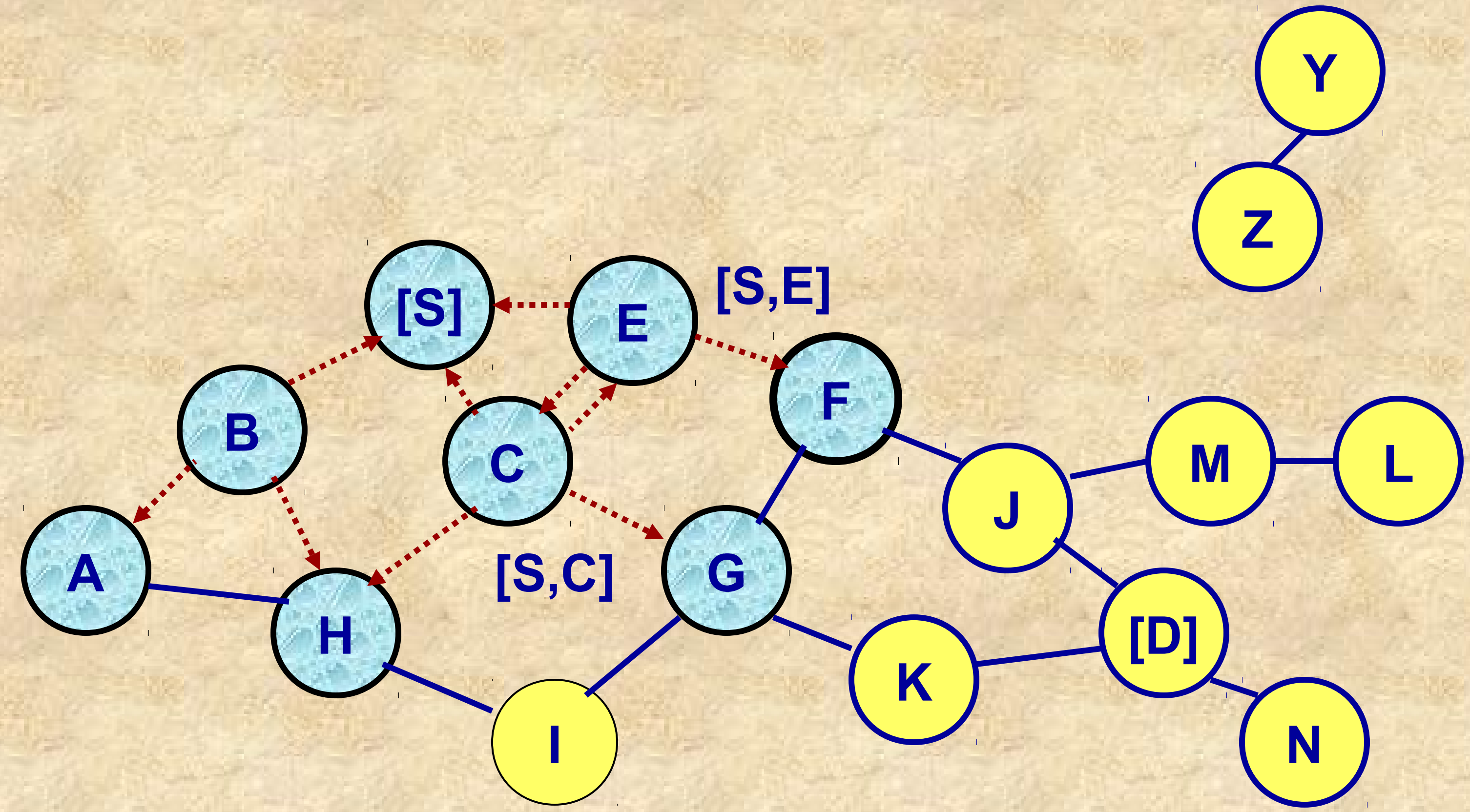
Broadcast transmission



Represents transmission of RREQ

[S] Represents the source; [D] represents the destination

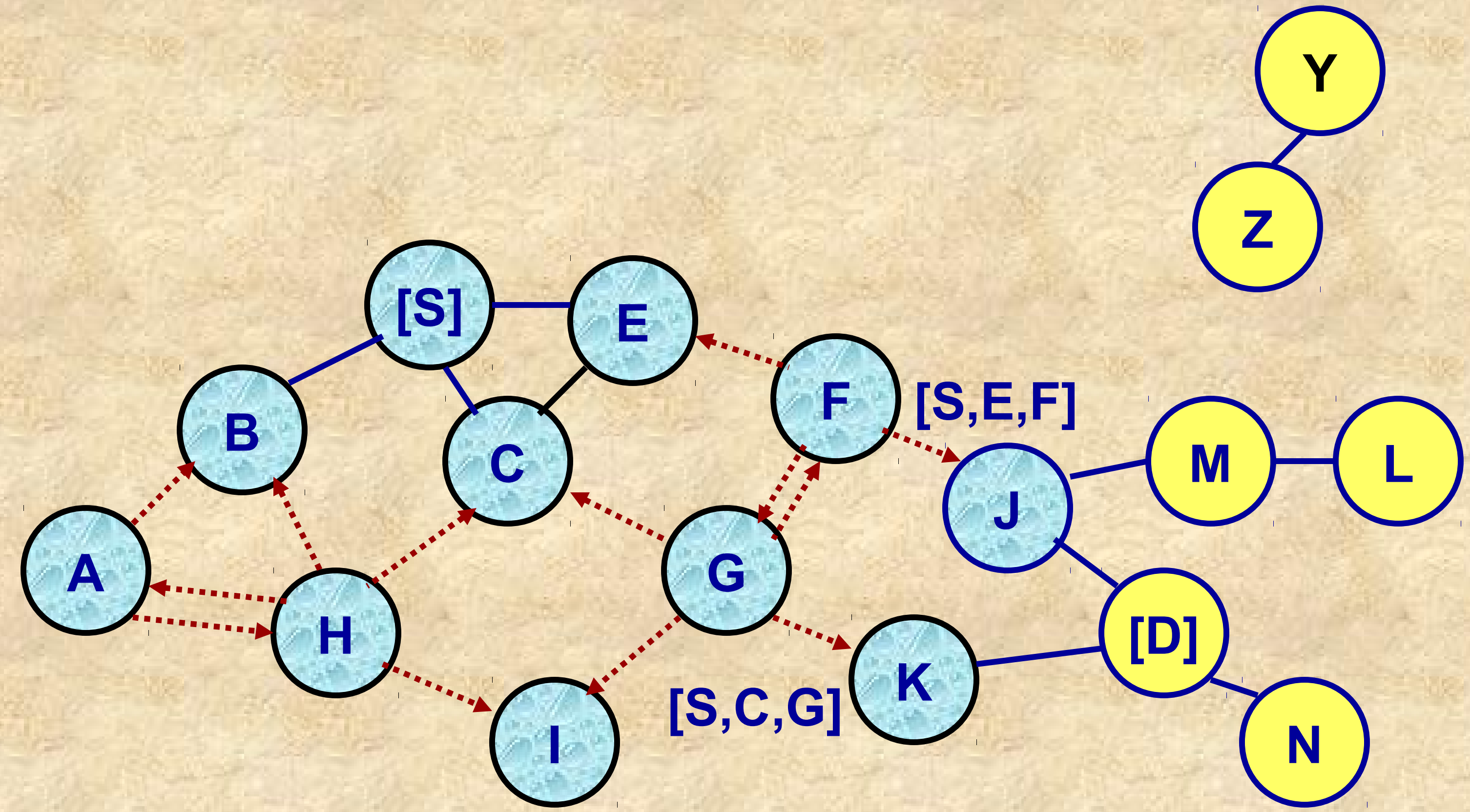
Route Discovery in DSR



- Node H receives packet RREQ from two neighbors: potential for collision

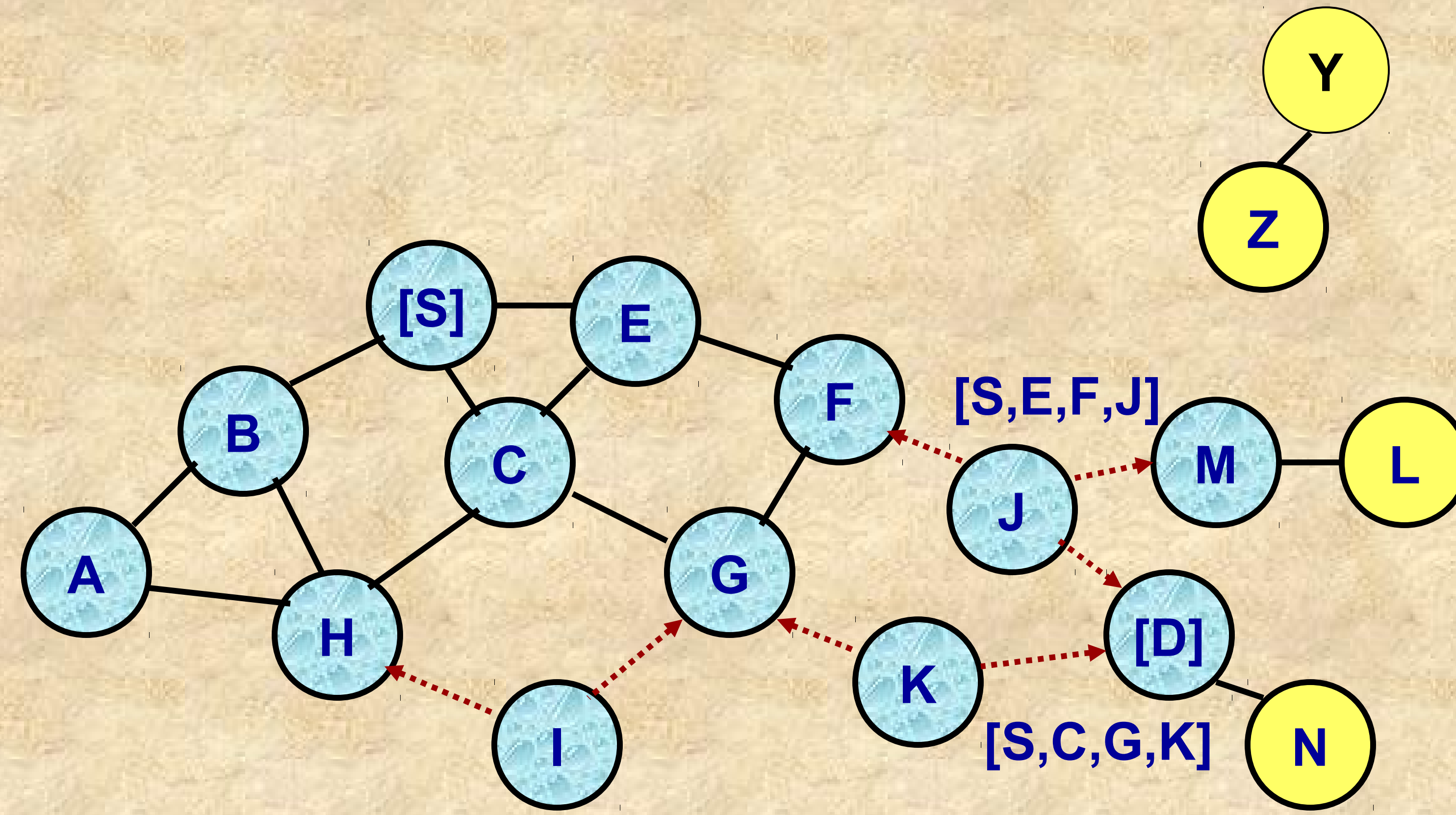
[X,Y] Represents list of identifiers appended to RREQ

Route Discovery in DSR



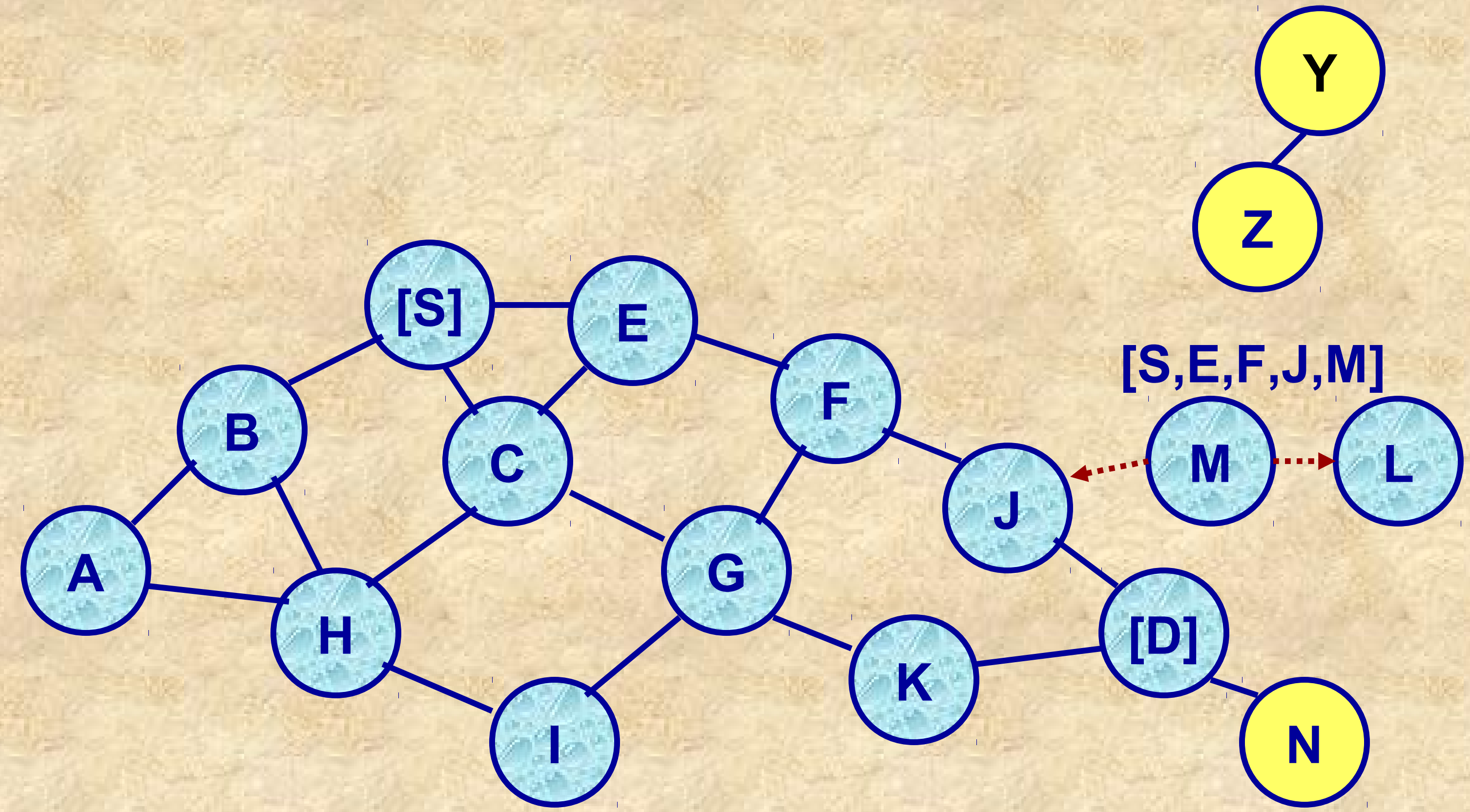
- Node C receives RREQ from G and H, but does not forward it again, because node C has already forwarded RREQ once

Route Discovery in DSR



- Nodes J and K both broadcast RREQ to node D
- Since nodes J and K are hidden from each other, their transmissions may collide

Route Discovery in DSR

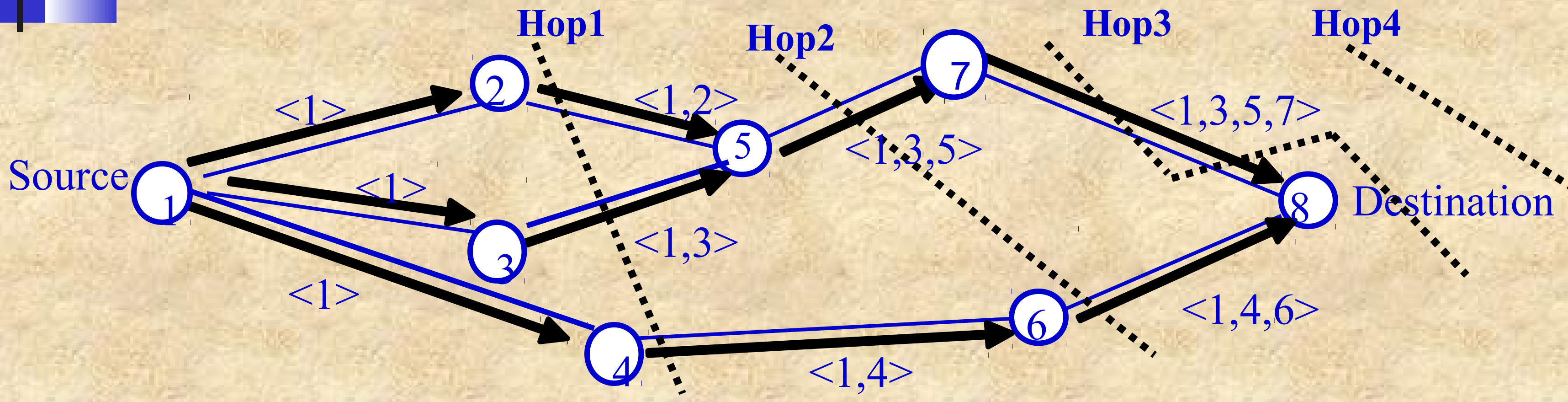


- Node D does not forward RREQ, because node D is the intended target of the route discovery

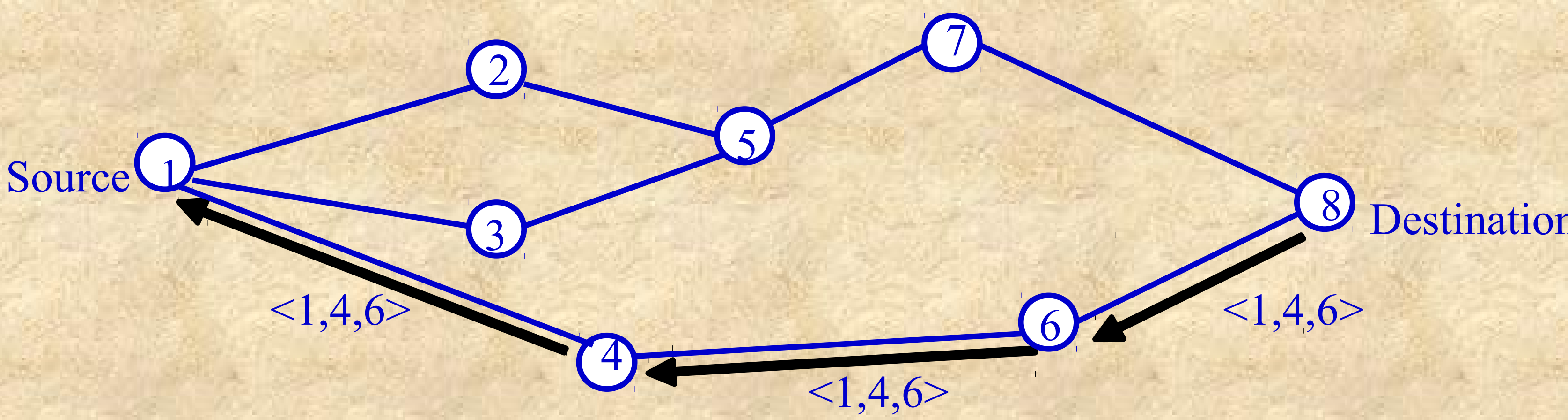
Route Discovery in DSR

- Destination D on receiving the first RREQ, sends a Route Reply (RREP)
- RREP is sent on a route obtained by reversing the route appended to received RREQ
- RREP includes the route from S to D on which RREQ was received by MH (node) D

Route Discovery in DSR



(a) Building Record Route During Route Discovery



(b) Propagation of Route Reply with the Route Record

Route Discovery in DSR

- AODV supports the use of symmetric channels
- If a source MH moves, it reinitiates route discovery protocol to find a new route
- If a MH along the route moves, its upstream neighbor notices the move and propagates a link failure notification message to each of its active upstream neighbors
- These MHs propagate link failure notification to their upstream neighbors, until the source MH is reached
- Hello messages can be used to maintain the local connectivity in the form of beacon signals
- Designed for unicast routing only, and multi-path is not supported

Temporarily Ordered Routing Algorithm (TORA)

- **TORA is a highly adaptive loop-free distributed routing algorithm based on the concept of link reversal**
- **TORA minimizes reaction due to topological changes**
- **Algorithm tries to localize messages in the neighborhood of changes**
- **TORA exhibits multipath routing capability**
- **Can be compared with water flowing downhill towards a sink node**
- **The height metric is used to model the routing state of the network**
- **Nodes maintain routing information to one-hop neighbors**

TORA (Cont'd)

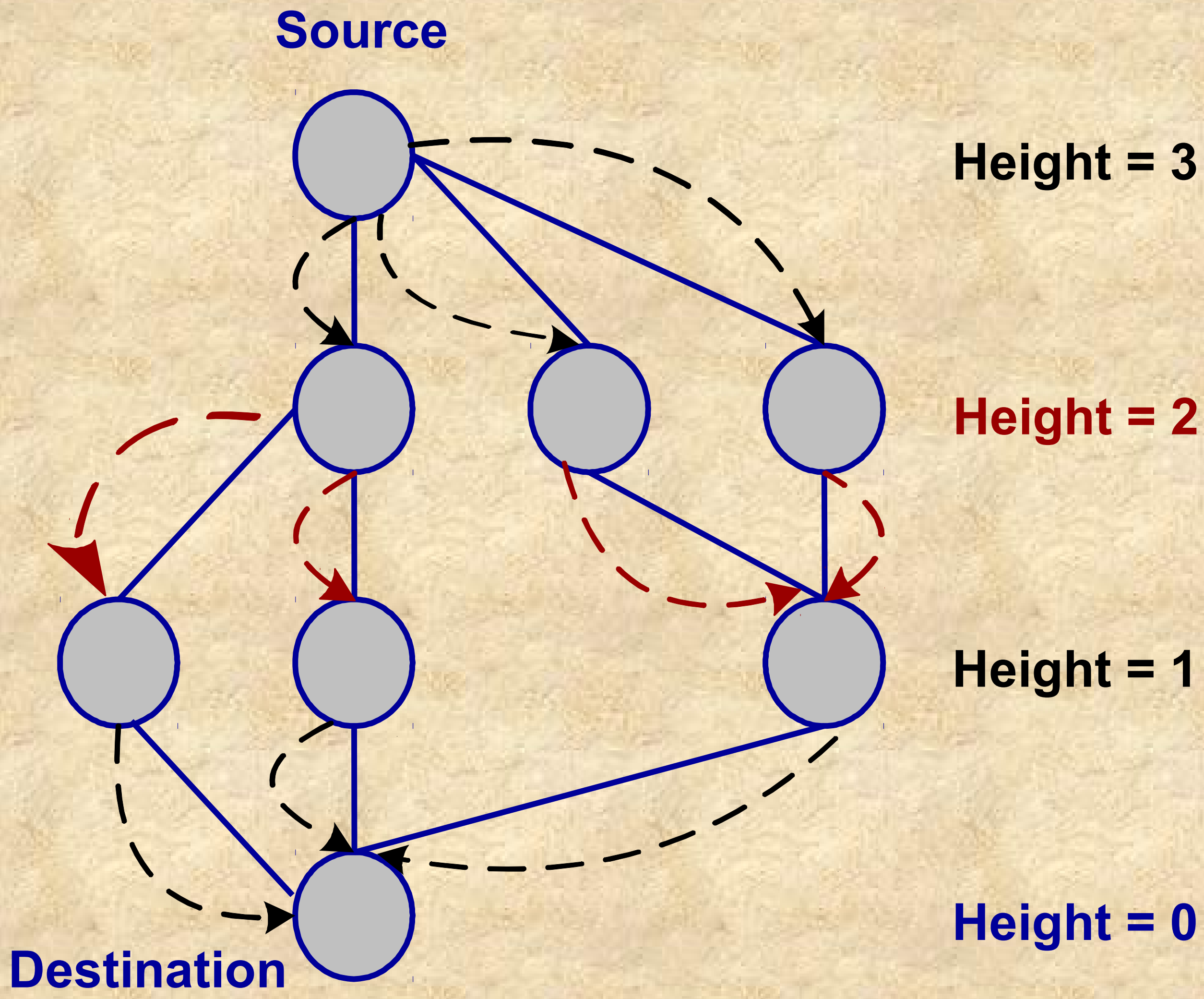
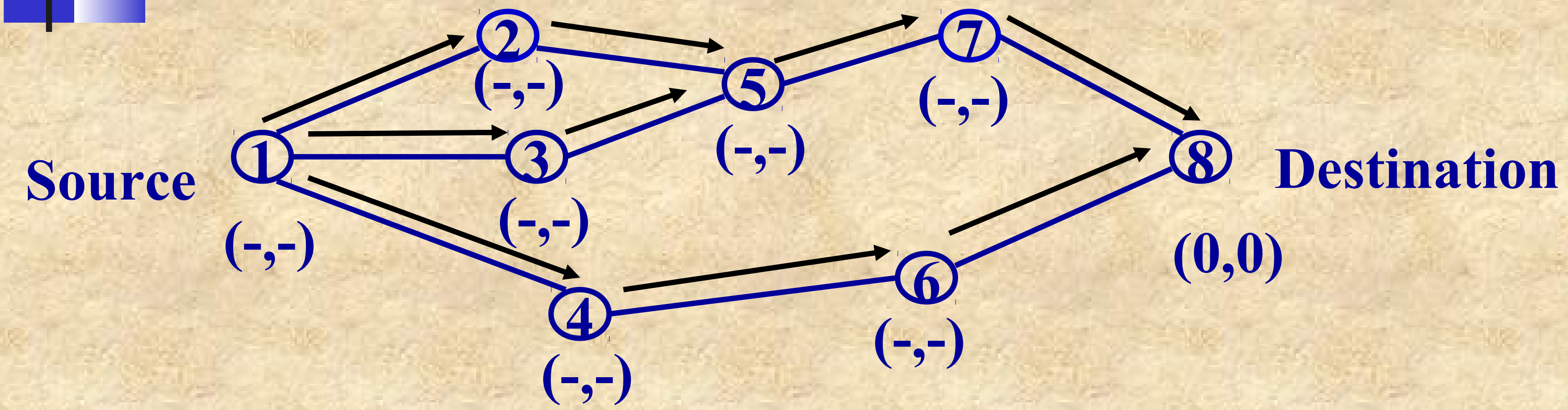


Illustration of TORA height metric

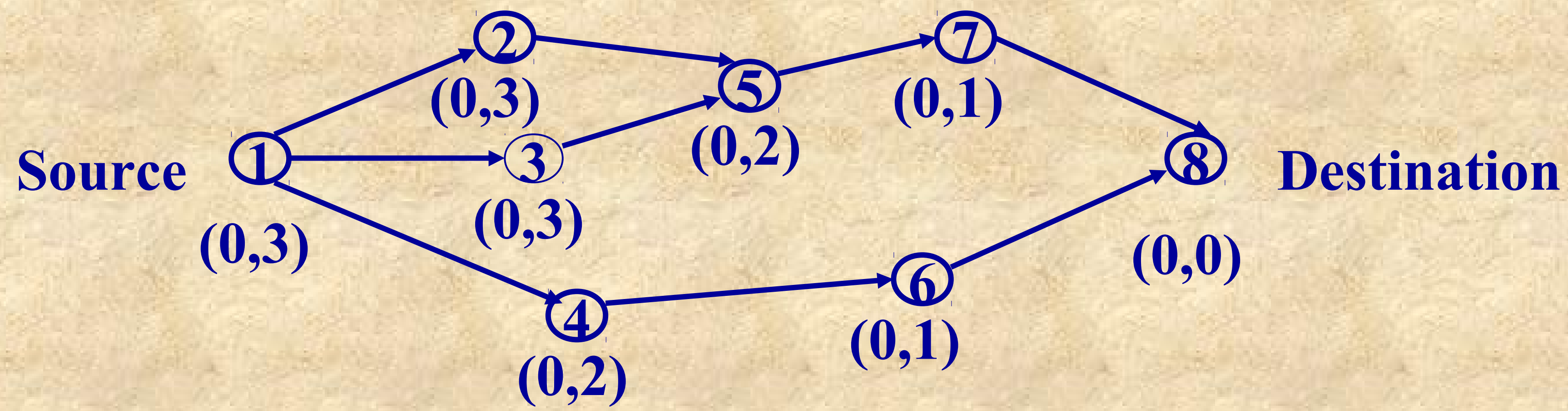
TORA (Cont'd)

- The protocol performs three basic functions:
  - Route creation
  - Route maintenance
  - Route erasure
- A separate directed acyclic graph (DAG) is maintained by each node (MH) to every destination
- Route query propagates through the network till it reaches the destination or an intermediate node containing route to destination
- This node responds with update and sets its height to a value greater than its neighbors
- When a route to a destination is no longer valid, it adjusts its height
- When a node senses a network partition, it sends CLEAR packet to remove invalid routes
- Nodes periodically send BEACON signals to sense the link status and maintain neighbor list

TORA (Cont'd)



Propagation of the query message

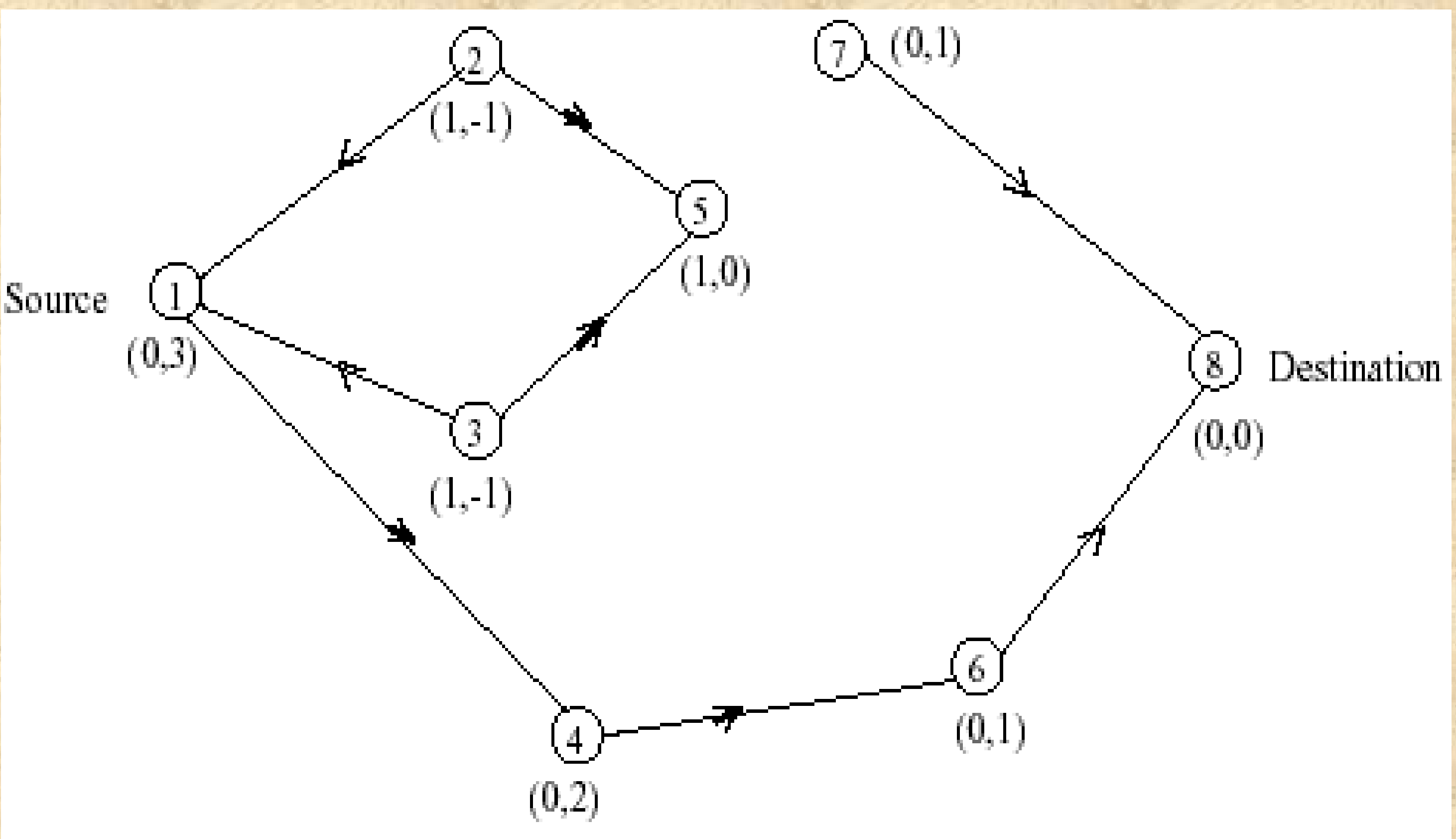


Node's height updated as a result of the update message

TORA Characteristics

- The height metric in TORA depends on logical time of a link failure
- The algorithm assumes all nodes to be synchronized
- TORA has 5-tuple metric:
  - Logical time of link failure
  - Unique ID of the node that defined the new reference level
  - A reflection indicator bit
  - A propagation ordering parameter
  - Unique ID of the node
- The first three elements together describe the reference level
- Oscillation can occur using TORA, similar to count-to-infinity problem
- TORA is partially reactive and partially proactive

Route Maintenance in TORA

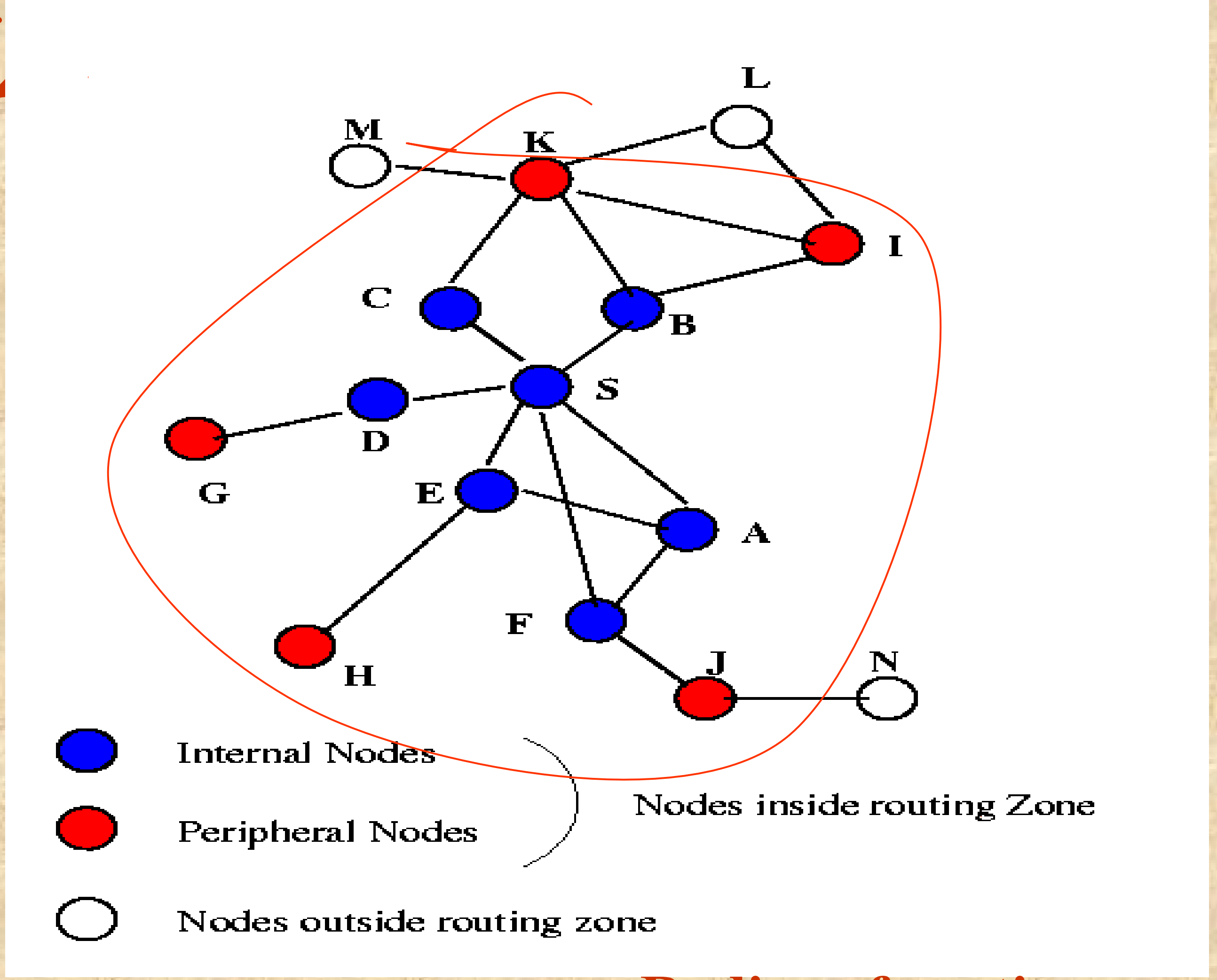


Hybrid Routing Approaches

Zone Routing Protocol (ZRP):

- **Hybrid of reactive and proactive protocols**
- **Limits the scope of proactive search to the node's local neighborhood**
- **The node need to identify all its neighbors which are one hop away**
- **Nodes local neighborhood is defined as a routing zone with a given distance**
- **All nodes within hop distance at most *d* from a node X are said to be in the routing zone of node X**
- **All nodes at hop distance exactly *d* are said to be peripheral nodes of node X's routing zone**
- **Intra-zone routing: Proactively maintain routes to all nodes within the source node's own zone**
- **Inter-zone routing: Use an on-demand protocol (similar to DSR or AODV) to determine routes to outside zone**

Zone Routing Protocol (



Radius of routing zone = 2

Hybrid Routing Approaches

- Interzone routing protocol (IERP) is responsible
- Uses a query-response mechanism by exploiting the structure of the routing zone, through a process known as *bordercasting*
- Bordercast is more expensive than the broadcast flooding used in other reactive protocols as there are many more border nodes than neighbors
- Cost of bordercast redundancy reduced by suppressing mechanisms based on query detection, early termination and loopback termination
- Source generates a route query packet with source node's ID and request number
- Sequence of recorded node Ids specifies an accumulated route from the source to the current routing zone
- If the destination is in routing zone, a route reply is sent back to source, along the path specified by reversing the accumulated route
- If the destination does not appear in the node's routing zone, the node bordercasts the query to its peripheral nodes

Hybrid Routing Approaches

Fisheye State Routing (FSR):

- Uses a multi-level Fisheye scopes to reduce routing update overhead in large networks
- It helps to make a routing protocol scalable by gathering data on the topology, which may be needed soon
- FSR tries to focus its view on nearby changes by observing them with the highest resolution in time and changes at distant nodes

Hybrid Protocols

Landmark Routing (LANMAR) with group mobility:

- Combines the features of FSR and landmark routing
- Uses a landmark to keep track of each set of nodes that move together
- Borrows the notion of landmarks to keep track of logical subnets
- The MHs exchange the link-state and topological information only with their immediate neighbors
- It also piggybacks a distance vector with size equal to the number of logical subnets and thus landmark nodes
- A modified version of FSR used for routing by maintaining routing table within the scope and landmark nodes

Hybrid protocols

Cluster-based Routing (CBRP):

- This is a partitioning protocol emphasizing support for unidirectional links
- Each node (MH) maintains two-hop topology information to define clusters
- Each cluster includes an elected cluster head, with which each member node (MH) has a bi-directional link
- In addition to exchanging neighbor information for cluster formation, nodes must find and inform their cluster head(s) of status of "gateway" nodes
- Cluster infrastructure is used to reduce the cost of disseminating the request
- When a cluster head receives a request, it appends its ID and a list of adjacent clusters and rebroadcasts it
- Each neighboring node which is a gateway to one of these adjacent clusters unicasts the request to appropriate cluster head

An Overview of Protocol Characteristics

Routing Protocol	Route Acquisition	Flood for Route Discovery	Delay for Route Discovery	Multipath Capability	Upon Route Failure
DSDV	Computed a priori	No	No	No	Flood route updates throughout the network
WRP	Computed a priori	No	No	No	Ultimately, updates the routing tables of all nodes by exchanging MRL between neighbors
DSR	On-demand, only when needed	Yes, aggressive use of caching may reduce flood	Yes	Not explicitly, as the technique of salvaging may quickly restore a route	Route error propagated up to the source to erase invalid path
AODV	On-demand, only when needed	Yes, conservative use of cache to reduce route discovery delay	Yes	Not directly, however, multipath AODV (MAODV) protocol includes this support	Route error broadcasted to erase multipath
TORA	On-demand, only when needed	Usually only one flood for initial DAG construction	Yes, once the DAG is constructed, multiple paths are found	Yes	Error is recovered locally and only when alternative routes are not available
ZRP	Hybrid	Only outside a source's zone	Only if the destination is outside the source's zone	No	Hybrid of updating nodes' tables within a zone and propagating route error to the source

Position Based Routing

- Routing protocols that take advantage of location information
- Can be classified according to how many MHs have the service
- Forwarding decision by a MH is essentially based on the position of a packet's destination and the position of the MH's immediate one-hop neighbor

Position Based Routing

Three main packet forwarding schemes:

- **Greedy forwarding**
- **Restricted directional flooding**
- **Hierarchical approaches**
  - **For the first two, a MH forwards a given packet to one (greedy forwarding) or more (restricted directional flooding) one-hop neighbors**
  - **The selection of the neighbor depends on the optimization criteria of the algorithm**
  - **The third forwarding strategy forms a hierarchy in order to scale to a large number of MHs**

Position Based Routing

Classification criteria for existing approaches:

Location Service
- Some-for some
- Some-for-all
- All-for some
- All-for-all

+

Forwarding Strategy
- Greedy forwarding
- Restricted directional flooding
  - Next-hop selection
  - Recovery strategy
- Hierarchical

Location Services

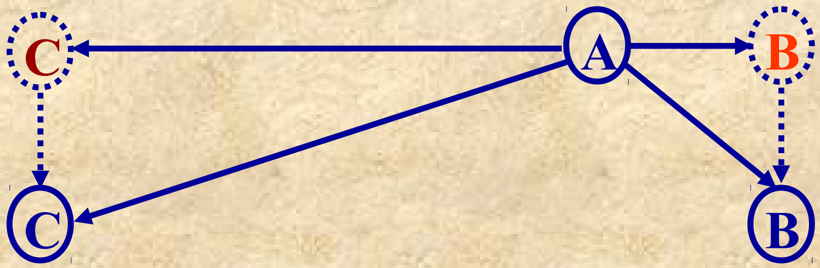
- **MHs register their current position with this service**
- **When a node does not know the position of a desired communication partner, it contacts the location service and requests that information**
- **In classical one-hop cellular network, there are dedicated position servers, with each maintaining position information about *all* MHs**
- **In MANETs, such centralized approach is viable only as an eternal service**
  - **First, it would be difficult to obtain the location of a position server if the server is a part of the MANET**
  - **Second, since a MANET is dynamic, it might be difficult to have at least one position server within a given MANET**

Distance Routing Effect Algorithm for Mobility

- **Within Distance Routing Effect Algorithm for Mobility (DREAM) framework, each MH maintains a position database that stores the location information about other MHs**
- **An entry in the position database includes a MH identifier, the direction of and distance to the MH, as well as a time value when this information has been generated**
- **A MH can control the accuracy of its position information available to other MHs in two ways:**
  - **By changing the frequency at which it sends position updates and is known as *temporal resolution***
  - **By indicating how far a position update may travel before it is discarded which is known as *spatial resolution***

Distance Effect in DREAM

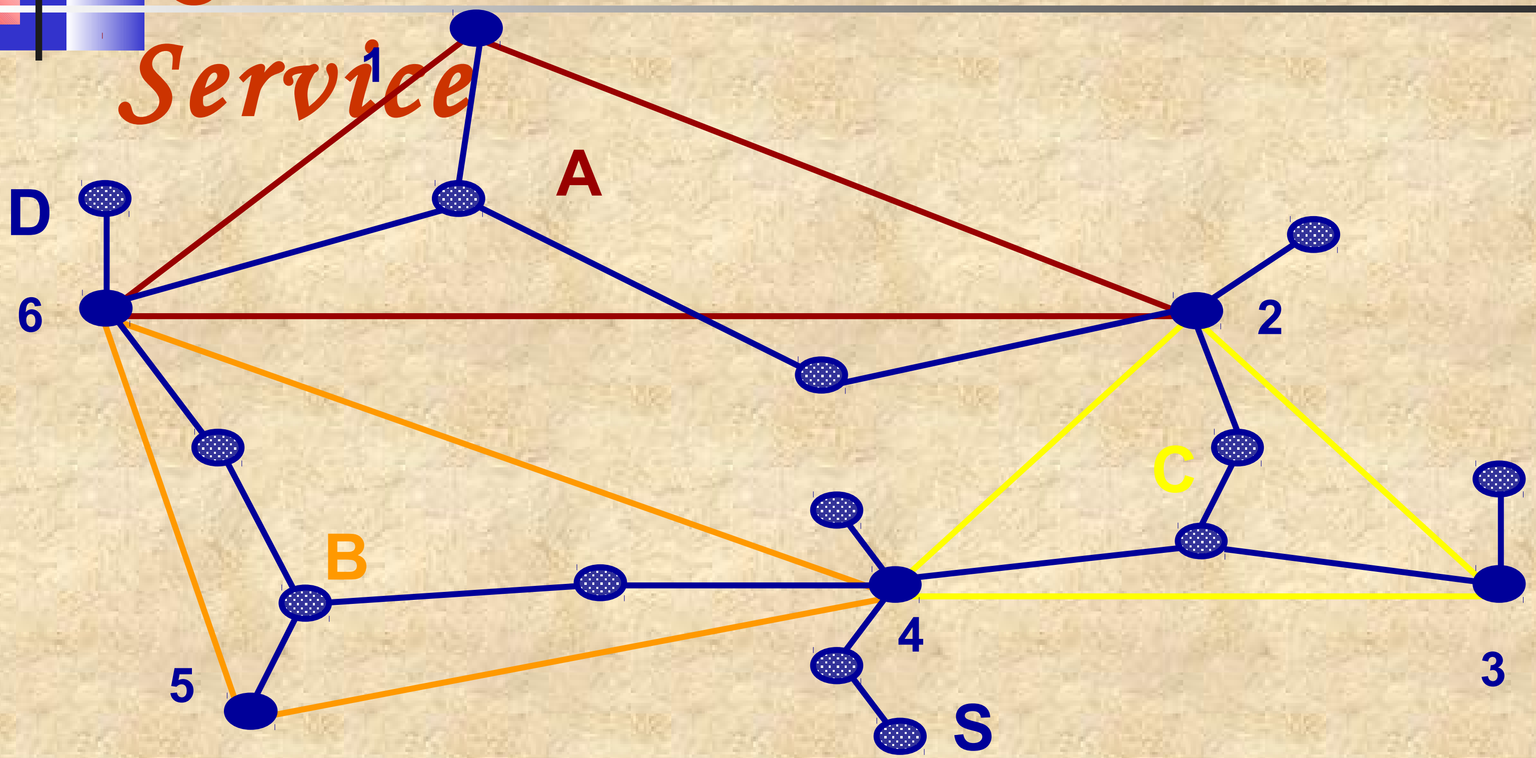
- Temporal resolution of sending updates is coupled with the mobility rate of a MH, i.e., the higher the speed is, more frequent the updates will be
- Spatial resolution is used to provide accurate position information in the direct neighborhood of a MH and less accurate information at nodes farther away
- Costs associated with accurate position information at remote MHs can be reduced since greater the distance separating two MHs is, slower they appear to be moving with respect to each other
  - For example, from MH A's perspective, the change in direction will be greater for MH B than for MH C



Quorum-Based Location Service

- **Information updates (write operations) are sent to a subset (quorum) of available nodes, and information requests (read operations) are referred to a potentially different subset**
- **When these subsets are designed such that their intersection is nonempty, it is ensured that an up-to-date version of the sought-after information can always be found**
- **A set of MHs is chosen to host position databases**
- **Next, a virtual backbone is constructed among the MHs of the subset by utilizing a non-position-based ad hoc routing algorithm**
- **A MH sends position update messages to the nearest backbone MH, which then chooses a quorum of backbone MHs to host the position information**

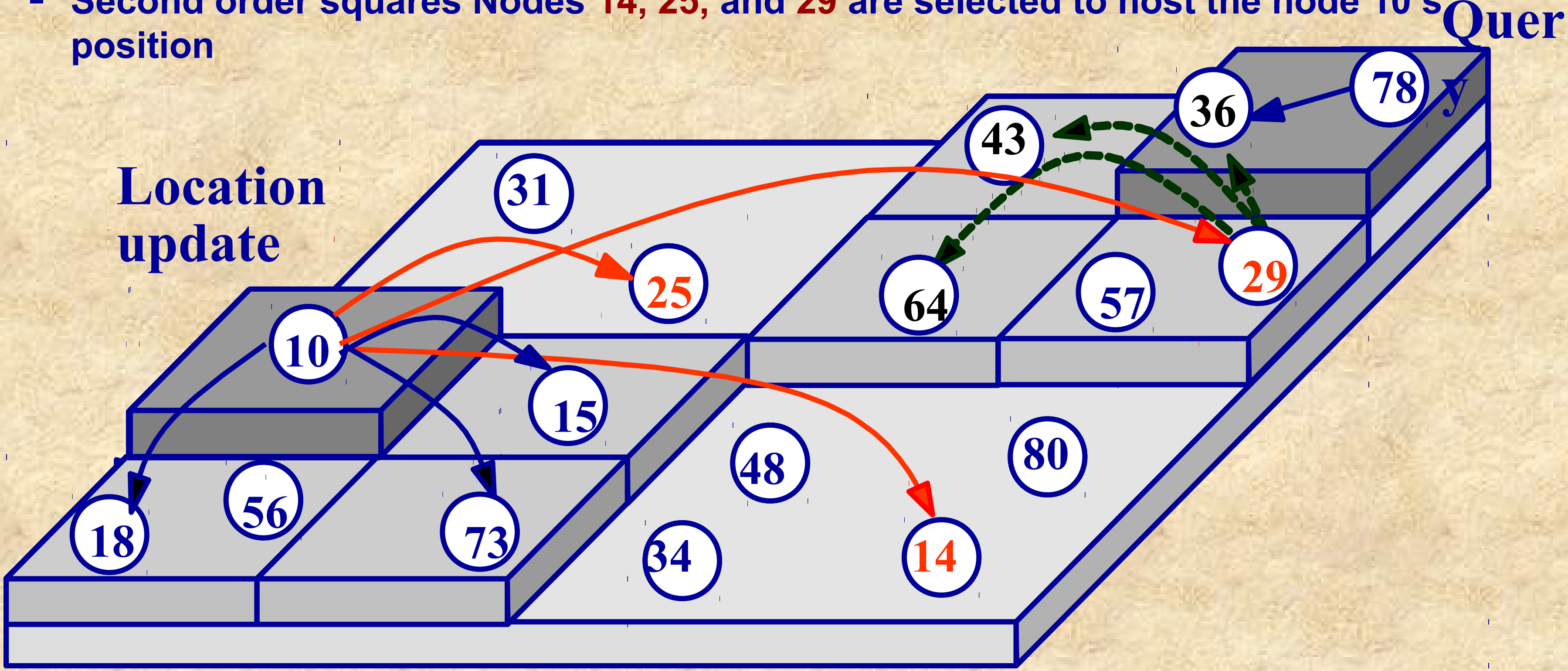
Quorum-Based Location Service



- MH D sends its updates to node 6, which might then select quorum A with nodes 1, 2, and 6 to host the information
- For example, MH 4 might, choose quorum B, consisting of MHs 4, 5, and 6 for the query
- Larger the quorum set is, higher the cost for position updates and queries are
- Can be configured to operate as all-for-all, all-for-some, or some-for-some approach

Grid Location Service

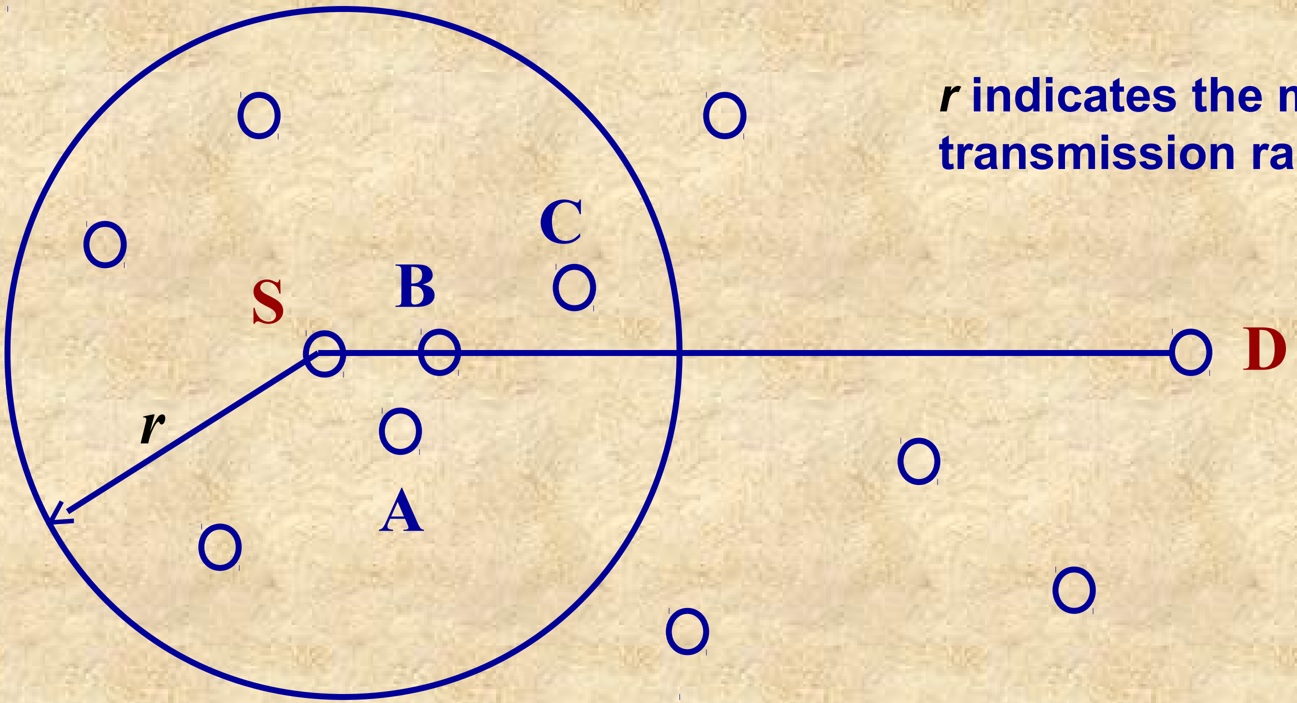
- Divides the area that contains the MANET into a hierarchy of squares, forming a so called *quad tree*
- Each node maintains a table of all other MHs within the local first-order square
- Establishes *near* MH IDs, defined as the least ID greater than a MH's own ID
- Position information of 10 is available at nodes 15, 18, 73
- Second order squares Nodes 14, 25, and 29 are selected to host the node 10's position



Homezone

- Two almost identical location services have been proposed independently
- Both use the concept of a virtual *Homezone* where position information for a node is stored
- By applying a well-known hash function to the node identifier, it is possible to derive the position *C* of the Homezone for a node
- All nodes within a disk of radius *R* centered at *C* have to maintain position information for the node

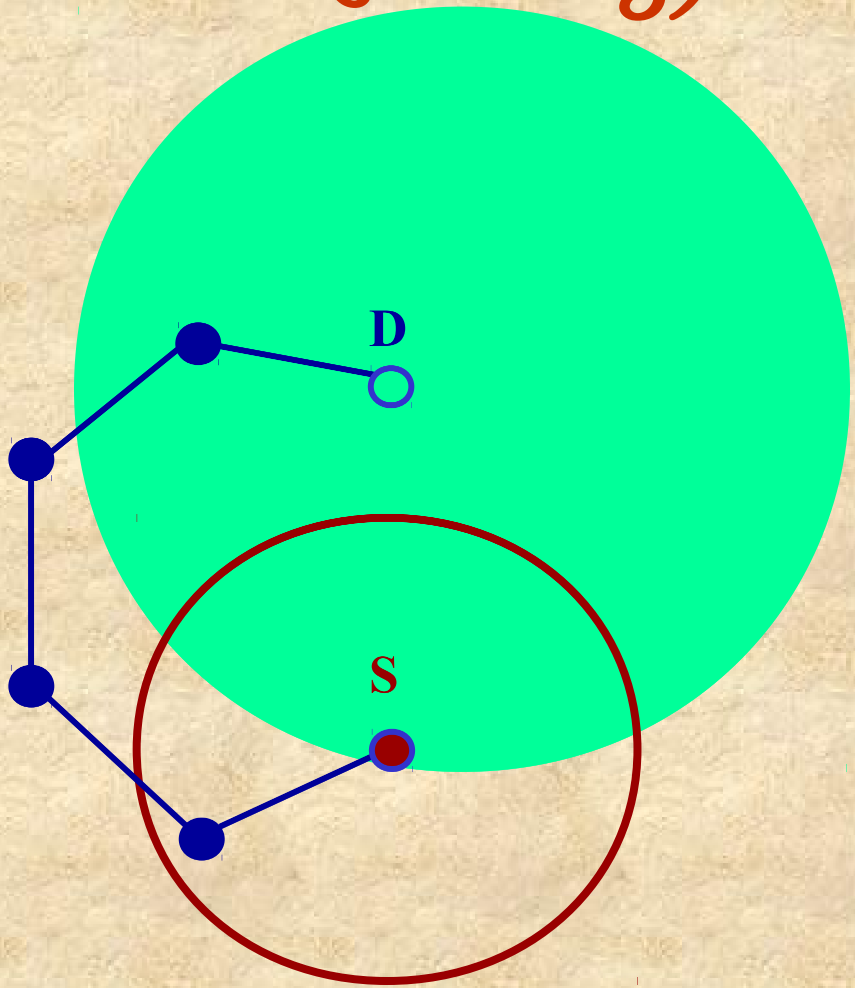
Greedy Packet Forwarding



r **indicates the maximum transmission range of node S**

- **Sender includes an approximate position of the recipient in the packet**
- **This information is gathered by an appropriate location service**
- **Intermediate node forwards packet to a neighbor lying in the direction of recipient**
- **This process can be repeated until recipient has been reached**
- **A good strategy when sender cannot adjust the transmission signal strength**

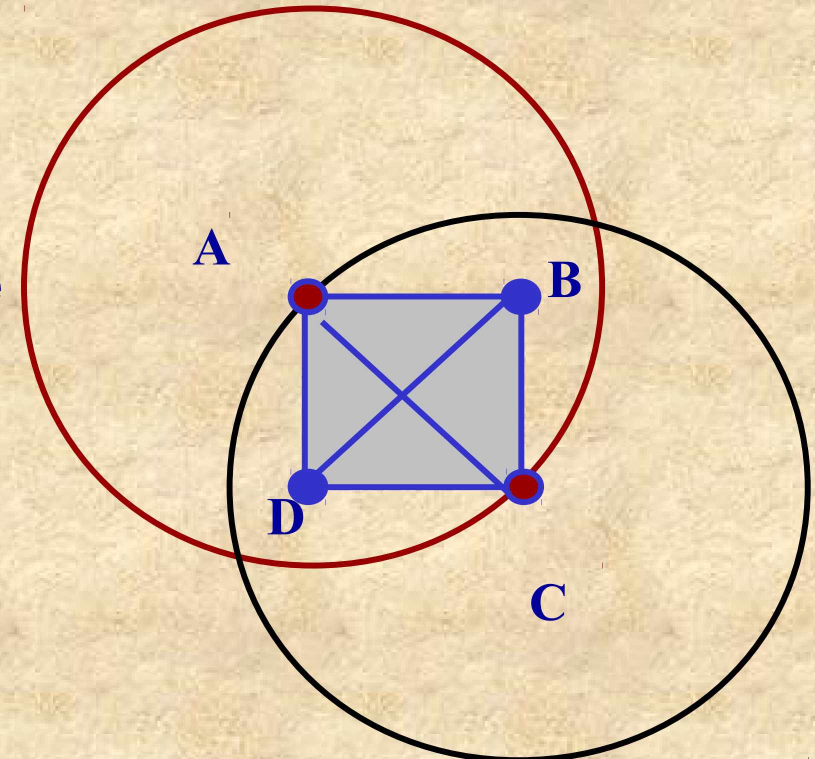
Greedy Packet Forwarding (Compass Routing)



- Forwarding packets in which the neighbor closer to the straight line between sender and destination is selected
- It is possible to let the sender randomly select one of the nodes closer to the destination than
- Greedy routing may fail to find a path between a sender and a destination, even though one does exist
- To counter this problem, the packet should be forwarded to the node with the least backward (negative) progress
- However, this raises the problem of looping

Greedy Perimeter Stateless Routing Protocol

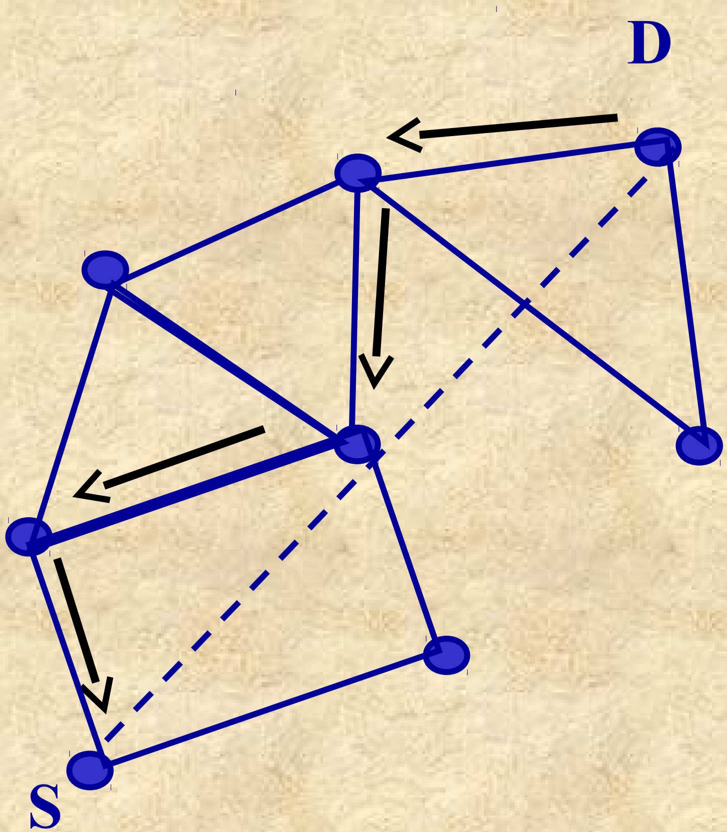
- Based on planar graph traversal
- Nodes do not have to store any additional information
- A packet enters the recovery mode when it arrives at a local maximum
- It returns to greedy mode when it reaches a node closer to the destination
- The graph formed by a MANET is generally not planar as shown



- An edge between two nodes A and B is included in the graph only if the intersection of the two circles with radii equal to the distance between node A and B around those two nodes does not contain any other nodes

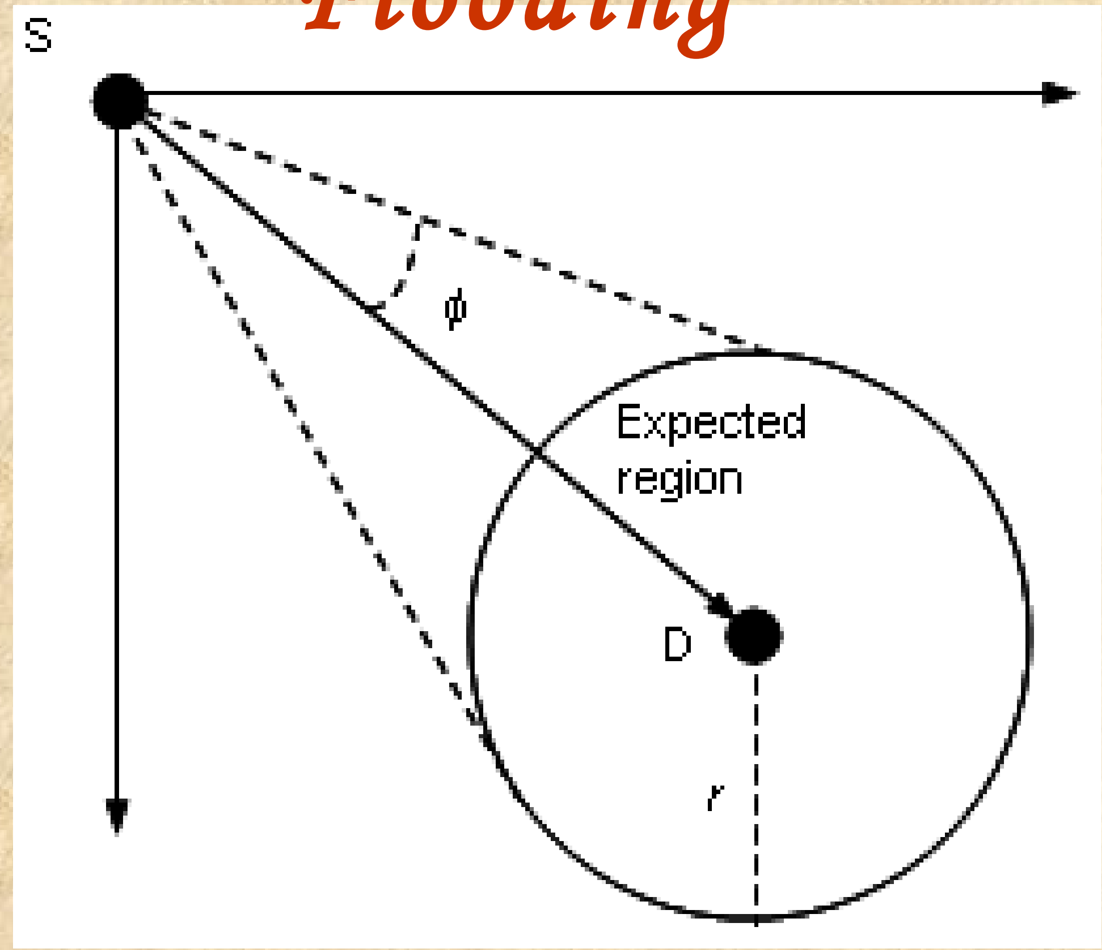
- The edge between nodes A and C would not be included in the planar subgraph since nodes B and D are contained in the intersection of the circles

Planar Graph Traversal



- A simple planar graph traversal is used to find a path toward the destination
- Forward packet on faces of planar subgraph progressively closer to the destination
- On each face from node S toward node D, the packet is forwarded along the interior of the face: forward the packet on the next edge counterclockwise from the edge on which it arrived
- Algorithm guarantees that a path will be found in case at least one exists
- The header of a packet contains additional information such as the position of the node, the position of the last intersection that caused a face change, and the first edge traversed on the current face

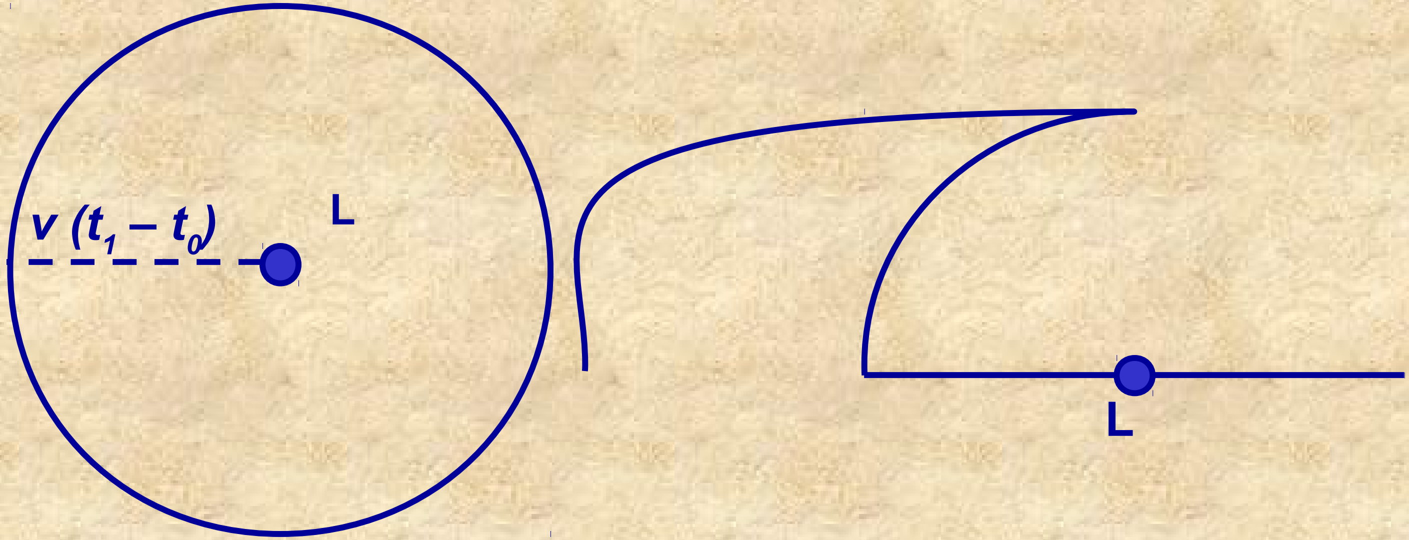
Restricted Directional Flooding



- Sender node S of a packet with destination node D forwards the packet to all one-hop neighbors that lie "in the direction of node D"
- *Expected region* is a circle around position of node D as it is known by node S
- "Direction towards node D" is defined by the line between nodes S and D and the angle ϕ

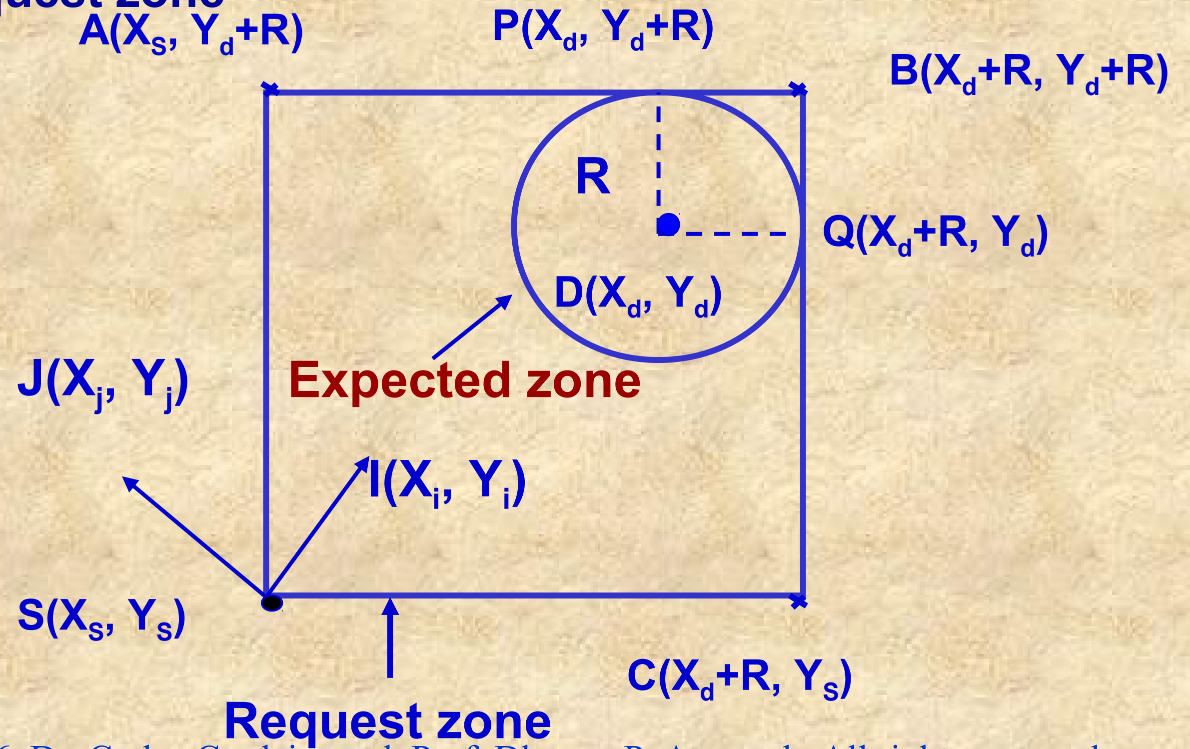
Expected Zone Routing

- Location-Aided Routing (LAR) uses position information to enhance the route discovery phase of reactive ad hoc routing approaches
- LAR uses this position information to restrict the flooding to a certain area called request zone at the time of route discovery
- If node S knows that node D travels with average speed *v*, then the expected zone is the circular region of radius $v(t_1 - t_0)$, centered at location L
- Expected zone is only an estimate made by node S to determine a region that potentially contains D at time t_1



Expected Zone Routing

- Request zone can be defined based on the expected zone
- Node S defines a *request zone* for the route request
- A node forwards a route request *only if* it belongs to the request zone
- To increase the probability to reach node D, the request zone should include the *expected zone*
- Additionally, the request zone may also include other regions around the request zone



Relative Distance Micro-Discovery Ad Hoc Routing

- Relative Distance Micro-discovery Ad Hoc Routing (RDMAR) routing protocol, an adaptive and scaleable routing protocol, is well suited in large mobile networks whose rate of topological changes is moderate
- Design is a typical localized reaction to link failures in a very small region of the network near the change
- Desirable behavior is achieved through the use of a flooding mechanism for route discovery, called Relative Distance Micro-discovery (RDM)
- An iterative algorithm calculates an estimate of their RD given their previous RD, an average nodal mobility and information about the elapsed time since they last communicated
- Query flood is then localized to a limited region of the network centered at the source node of the route discovery and with maximum propagation radius that equals to the estimated relative distance

Relative Distance Micro-Discovery Ad Hoc Routing

- Packets are routed between the stations of the network by using routing tables which are stored at each station
- Each routing table lists all reachable destinations, wherein for each destination *j*, it includes: the "D*efault Router*" field
- "*Time_Last_Update*" (TLU) field that indicates the time since the node last received routing information for *j*
- "*RT_Timeout*" field which records the remaining amount of time before the route is considered invalid
- "R*oute Flag*" field which declares whether the route to *j* is active

Two main algorithms are:

- Route Discovery
  - When an incoming call arrives at node *i* for destination node *j* and there is no route available, *i* initiates a route discovery phase
  - Either to flood the network or limit discovery in a smaller region of the network
- Route Maintenance
  - Upon receipt of a data packet, first processes the routing header, forwards the packet to the next hop, and send an explicit message to examine whether a bi-directional link can be established with the previous node

Hierarchical Routing

Complexity of the routing algorithm can be reduced tremendously by establishing some form of hierarchy

Terminodes Routing

- Combines hierarchical and position-based routing with two levels of hierarchy
- Packets are routed according to a proactive distance vector scheme if the destination is close to the sending node
- Once a long distance packet reaches the area close to the recipient, it continues to be forwarded by means of the local routing algorithm
- To prevent greedy forwarding, the sender includes a list of positions in the packet header

Grid Routing

- Position-based hierarchical routing
- A proactive distance vector routing protocol is used at the local level, while position-based routing is employed for long-distance packet forwarding
- Packets that are addressed to a position-unaware node arrives at a position-aware proxy
- Then forwarded according to the information of the proactive distance vector protocol
- As a repair mechanism for greedy long-distance routing, a mechanism called Intermediate Node Forwarding (INF) is proposed
- If a forwarding node has no neighbor with forward progress, it discards the packet and sends a notification to the sender of the packet

Other Position-based Routing

The GPS-based systems do not provide good accuracy inside the building and the surrounding area can be classified in the following five categories:

- Typical office environment with no line-of-sight (NLOS) with 50ns delay spread
- Large open space with 100ns delay spread with NLOS
- Large indoor or outdoor space with 150ns delay spread with NLOS
- Large indoor or outdoor space with line-of-sight and 140ns delay spread
- Large indoor or outdoor space with NLOS and 250ns delay spread

Comparison of Location Services

Criterion	DREAM	Quorum system	GLS	Homezone
Type	All-for-all	Some-for-some	All-for-some	All-for-some
Communication complexity (update)	O(n)	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Communication complexity (lookup)	O(c)	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Time complexity (update)	O(n)	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
Time complexity (lookup)	O(c)	$O(\sqrt{n})$	$O(\sqrt{n})$	$O(\sqrt{n})$
State volume	O(n)	O(c)	O(log(n))	O(c)
Localized information	Yes	No	Yes	No
Robustness	High	Medium	Medium	Medium
Implementation complexity	Low	High	Medium	Low

Comparison of location services

- **DREAM is fundamentally different from other position services, as it requires all MHs to maintain position information about every other MH**
- **The time required to perform a position update in DREAM is a linear function of the diameter of the network, leading to a complexity of O($\sqrt{n}$)**
- **Quorum system requires the same operations for position updates and position lookups**
- **Quorum system depends on a non-position-based ad hoc routing protocol**
- **Each node in GLS and Homezone selects a subset of all available nodes as position servers**

Comparison of forwarding schemes (n = number of nodes)

Criterion	Greedy	DREAM	LAR	Terminodes	Grid
Type	Greedy	Restricted directional flooding	Restricted directional flooding	Hierarchical	Hierarchical
Communication complexity	O($\sqrt{n}$)	O(n)	O(n)	O($\sqrt{n}$)	O($\sqrt{n}$)
Tolerable position inaccuracy	Transmission range	Expected region	Expected region	Short-distance routing range	Short-distance routing range
Requires all-for-all location service	No	Yes	No	No	No
Robustness	Medium	High	High	Medium	Medium
Implementation complexity	Medium	Low	Low	High	High

Summary of Forwarding Schemes

- *Communication complexity* indicates the average number of one-hop transmissions required to send a packet from one node to another node with known position
- Need to tolerate *different degrees of inaccuracy* with regard to the position of the receiver
- Forwarding *requires all-for-all location service* criterion
- *Robustness* is high if the failure of a single MH does not prevent the packet from reaching its destination
- *Greedy forwarding* is efficient, with a communication complexity of O($\sqrt{n}$), and is well suited for use in MANETs with a highly dynamic topology
- The *face-2 algorithm* and the *perimeter routing* of GPSR are currently the most advanced recovery strategies
- *Restricted directional flooding*, as in DREAM and LAR, has communication complexity of O(n) and therefore does not scale well for large networks with a high volume of data transmissions

Signal Stability Routing Protocol

- On-demand Signal Stability-Based Adaptive Routing protocol (SSR) selects routes based on the signal strength (weak or strong) between nodes and a node's location stability
- The net effect is to choose routes that have "stronger" connectivity
- Two cooperative protocols used: Dynamic Routing Protocol (DRP) and Static Routing Protocol (SRP)
- DRP is responsible for the maintenance of Signal Stability Table (SST) and the Routing Table (RT)
- DRP passes the packet to the SRP which passes the packet up the stack if it is the intended receiver, or looks up in the routing table for the destination
- If no entry is found in the routing table, a route search process is initiated
- If there is no route reply received at the source within a specified timeout period, the source changes the PREF field in the packet header to indicate that weak channels have been accepted

Other Routing Protocols

Power Aware Routing

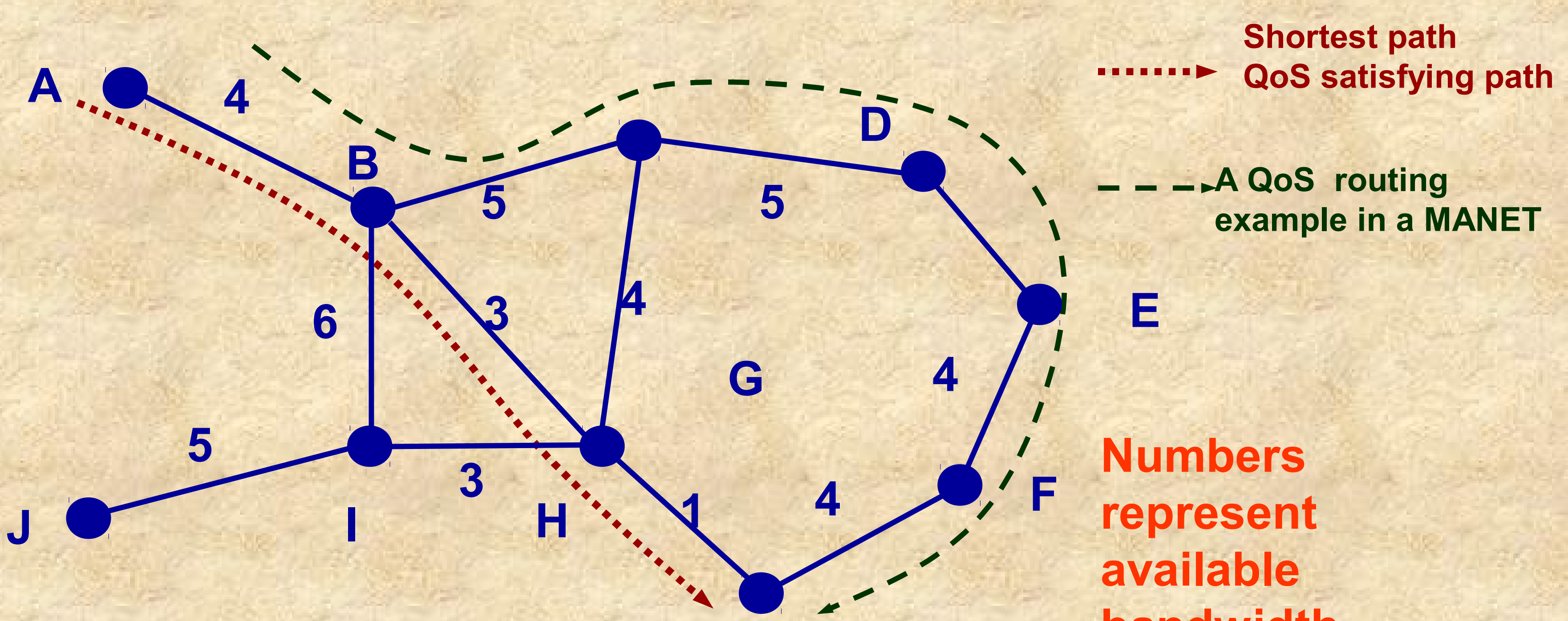
- **Power-aware metrics are used for determining routes in MANETs**
- **A shortest-cost routing algorithm reduces the cost/packet of routing packets by 5 - 30 percent over shortest-hop routing**
- **Mean time to node failure is increased significantly, while packet delays do not increase**

Associativity-Based Routing

- **Objective: to derive long-lived routes for ad hoc networks**
- **A route is selected based on a metric that is known as the degree of association stability**
- **Periodically generated beacon signifies existence**
- **The three phases are: Route discovery; Route reconstruction (RRC); and Route deletion**
- **RRC may consist of partial route discovery, invalid route erasure, valid route updates, and new route discovery**

QoS Routing

- All routing protocols proposed either for routing along shortest available path or within some system-level requirement
- Such paths may not be adequate for QoS required applications
- Shortest path route A-B-H-G will have a lower bandwidth
- The path A-B-C-D-E-F-G will have a minimum bandwidth of 4



Core Extraction Distributed Ad Hoc Routing

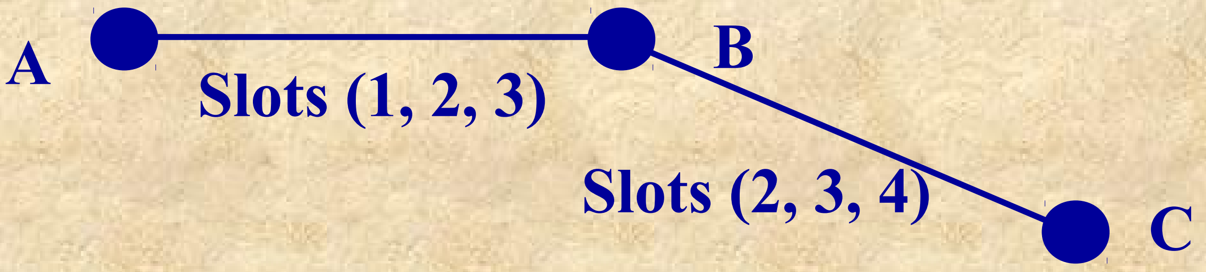
- **Core Extraction: A set of nodes is elected to form the core that maintains the local topology of the nodes in its domain and performs route computation**
- **Link State Propagation: Propagates bandwidth availability information of stable links to all core nodes**
- **Route Computation: Establishes a core path from the domain of the source to the domain of the destination**

Incorporating QoS in Flooding-based Route Discovery

- **To limit the amount of flooding, a logical ticket-based probing algorithm with imprecise state model for discovering a QoS-aware routing path**
- **A probing message is split into multiple probes and forwarded to different next-hops, with each child probe containing a subset of the tickets from their parents**
- **When one or more probe(s) arrive(s) at the destination, the hop-by-hop path known and delay/bandwidth information can be used to reserve QoS-satisfying path**

QoS support using Bandwidth Calculations

- Involves end-to-end bandwidth calculation and allocation
- Source node can determine the resource availability for supporting the required QoS
- Need to know how to assign the free slots at each hop
- Time slots 1, 2, and 3 are free between nodes A and B, and slots 2, 3, and 4 are free between nodes B and C
- There will be collisions at node B if node A tries to use all three slots 1, 2, and 3 to send data to node B while node B is using one or both slots 2 and 3 to send data to node C
- Need to divide common free slots 2 and 3 between the two links



Multi-path QoS Routing

- Suitable for ad hoc networks with very limited bandwidth for each path
- Algorithm searches for multiple paths for the QoS route
- Adopts the idea of ticket-based probing scheme
- Enhances routing resiliency by finding node/edge disjoint paths when link and/or node fail
- Another approach is to use extension of AODV to determine a backup source-destination routing path if the path gets disconnected frequently due to mobility or changing link signal quality
- A backup path can be easily piggybacked in data packets

Conclusions and Future Directions

- **Routing is undoubtedly the most studied aspect of ad hoc networks**
- **Yet, many issues remain open such as more robust security solutions, routing protocol scalability, QoS support, and so on ….**
- **Integration of MANETs and infrastructure-based networks such as the Internet will be an important topic in wireless systems beyond 3G**
- **Availability of Dynamic Host Configuration Protocol (DHCP) servers many not be practical to get IP addresses**
- **Nodes (MHs) have to resort to some heuristic to obtain their IP addresses**
- **Routing algorithms for MANETs are equally applicable to sensor networks except for low mobility, much larger number of sensor nodes and use of small battery**